Proton structure and hadronization at LHCb

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on behalf of the **LHCb** collaboration

Correlations in Partonic and Hadronic Interactions 2022

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Nonperturbative dynamics inside proton and hadronization at LHCb

- Precision measurements, proton structure and hadronization are main parts of QCD/EW program at LHCb.
- W mass, Z production, heavy quark PDFs …
- Jet substructure, jet fragmentation functions for light and heavy quarks and resonances.

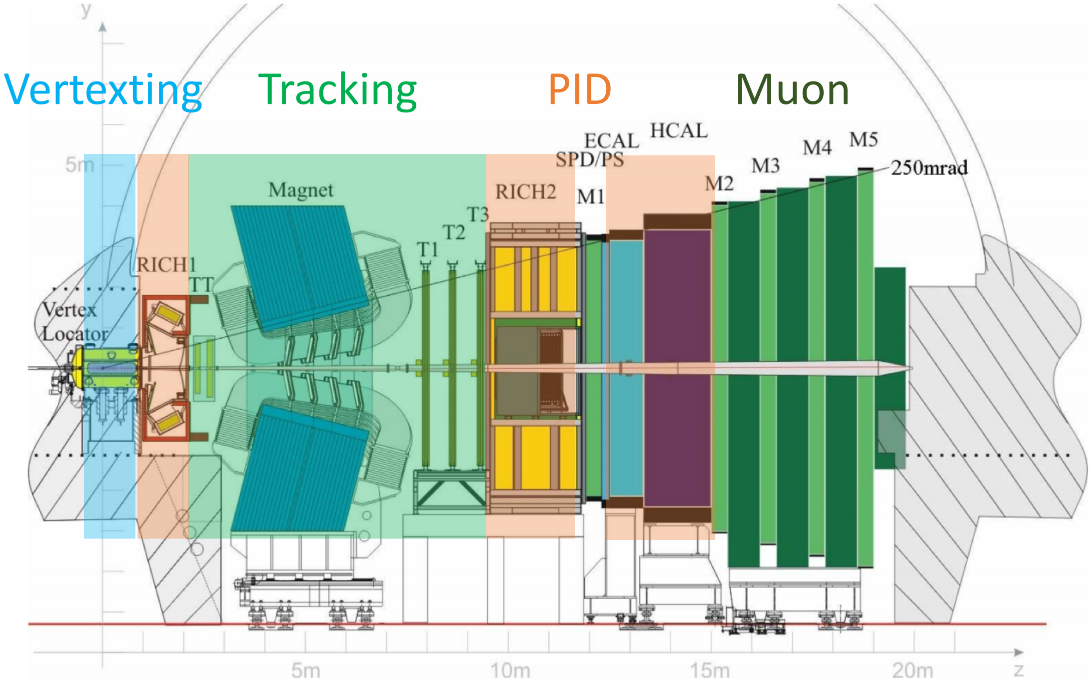
→ This talk presents new results in the following topics:

- ❑ Intrinsic charm in Z+c
- ❑ Angular correlations in DY – TMD PDF
- ❑ Multi-differential TMD JFF in Z+jet

The LHCb experiment

[JINST 3 (2008) S08005](#)
[Int. J. Mod. Phys. A 30 (2015) 1530022](#)

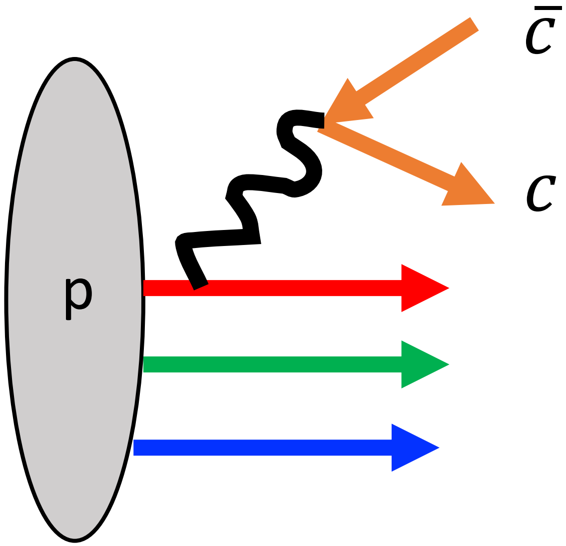
- General purpose detector in the forward region ($2 < \eta < 5$)
- Full jet reconstruction with tracking, ECAL and HCAL + Tagging of jets from light-quark, c- and b-quark
- Charged hadron identification
- Impact parameter resolution $15+29/p_T$ [GeV]
- Decay time resolution 45 fs
- Muon reconstruction for resonance states

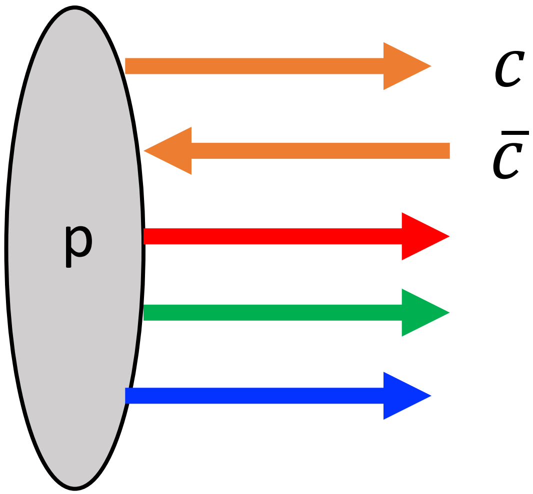


Physics at LHCb :

- Matter-antimatter symmetry
- CP Violation and rare decays of beauty and charm hadrons
- QCD, Electroweak and exotica ...

Is there charm in the proton?





Extrinsic

: Perturbative charm content via gluon radiation $g \rightarrow c\bar{c}$.

: Charm pairs created from DGLAP evolution.

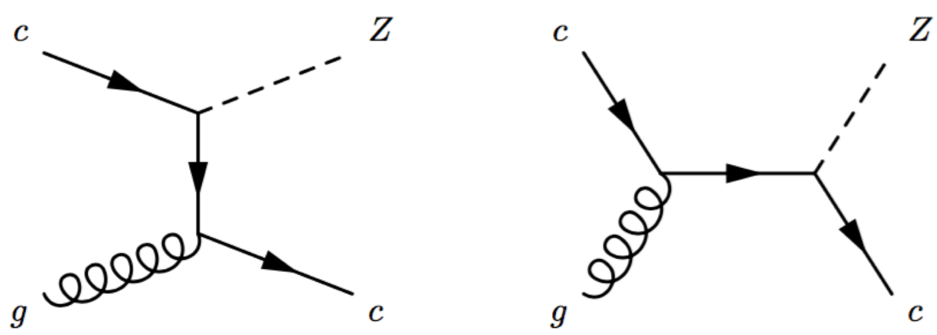
: Charm PDF will resemble gluon PDF, and decrease sharply at large x.

Intrinsic

: $|uudc\bar{c} >$ component allowed in the proton wave function .

: Both valance-like and sea-like charm possible.

Intrinsic charm at LHCb



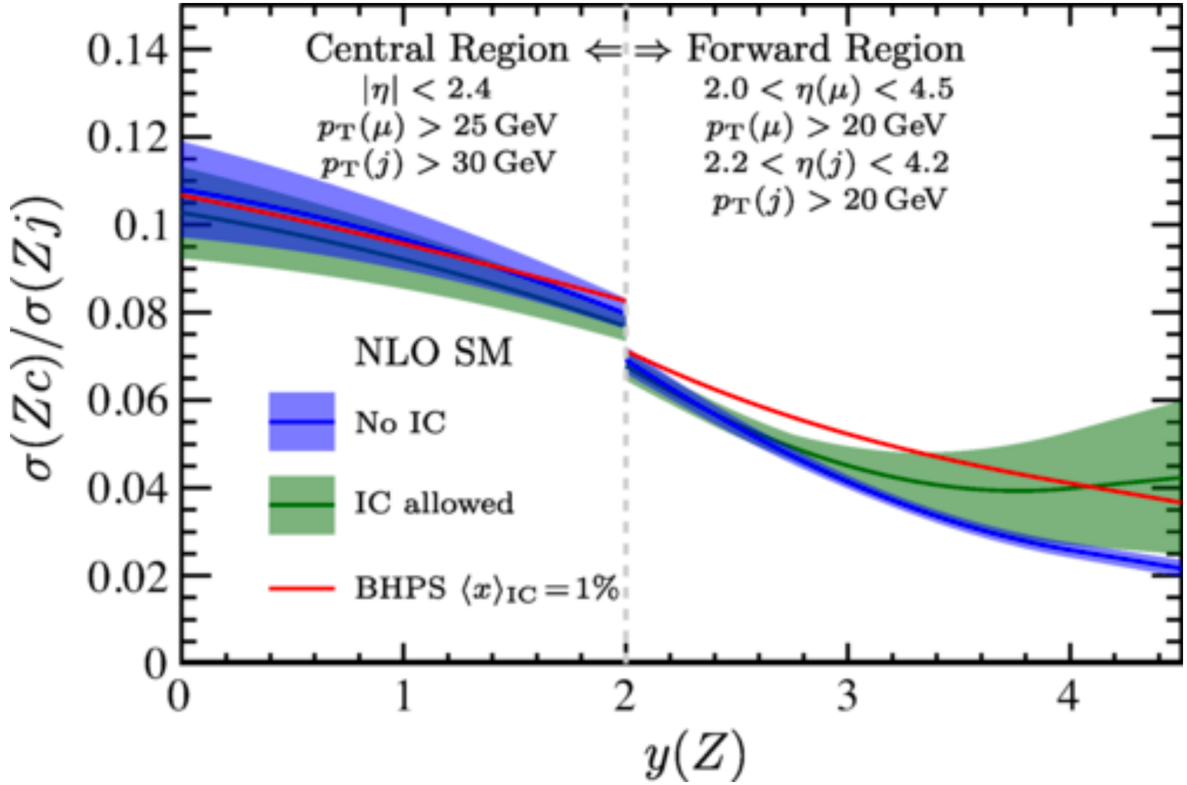
Leading order Zc production via gc → Zc scattering at LHCb

Phys. Rev. D **93**, 074008 (2016)

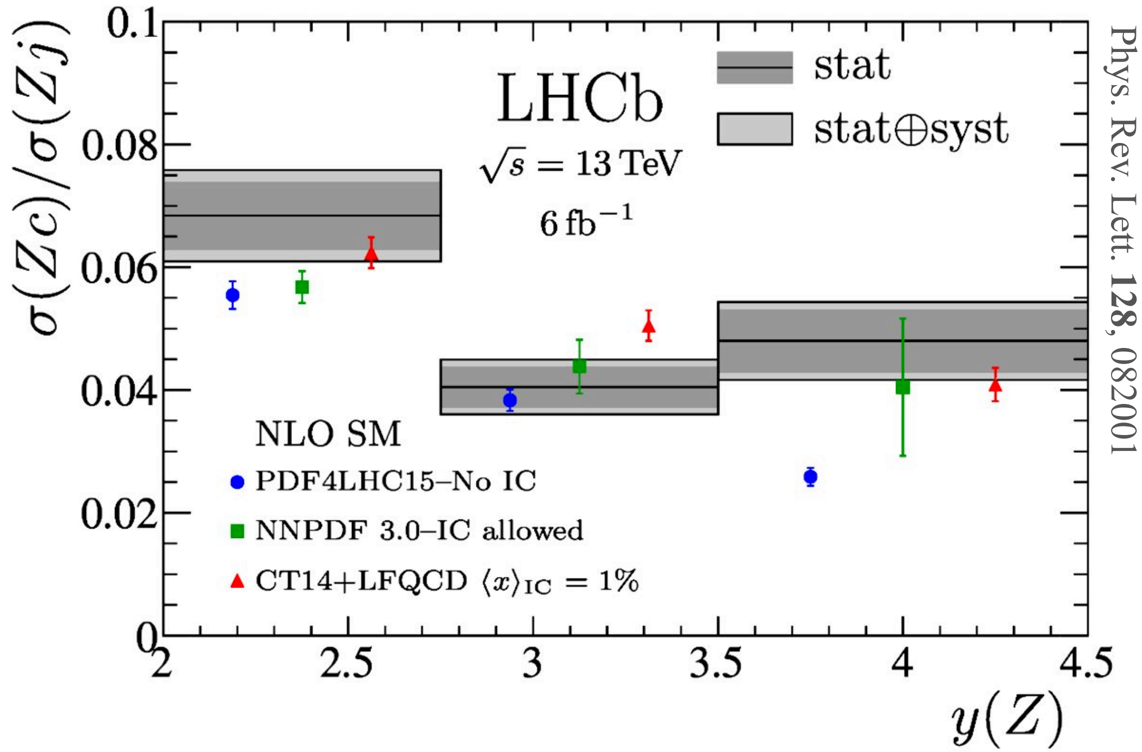
$$\mathcal{R}_j^c \equiv \sigma(Zc)/\sigma(Zj)$$

- $Z + c$ production at forward rapidity require one initial parton to have large momentum fraction x.
- $Z + c$ requires large momentum transfer Q above EW scale, hence small nuclear and hadronic effects.
- $Z + c$ to $Z + j$ ratio to reduce sensitivities to experimental and theoretical uncertainties.

Phys. Rev. Lett. **128**, 082001

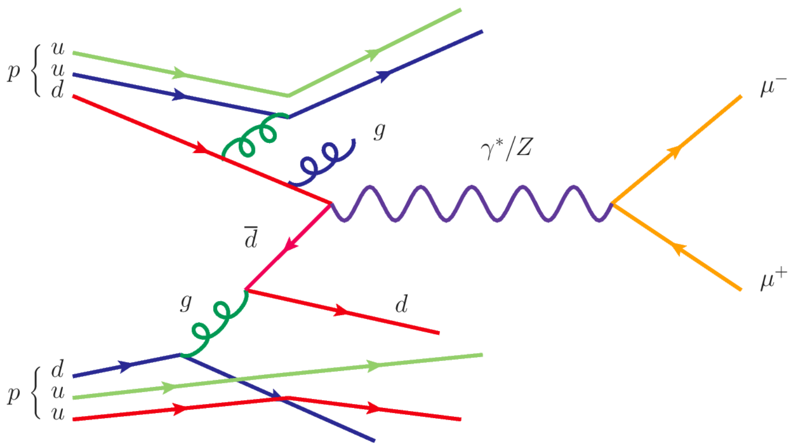


- Light Front QCD: Non-perturbative IC manifests as valence-like charm content in the parton distribution functions (PDFs) of the proton at large x.
- Perturbative charm content via gluon radiation $g \rightarrow c\bar{c}$ is expected to be suppressed at large x, at forward rapidity.
- A percent-level valence-like IC contribution would produce a clear enhancement in R_j^c for large (more forward) values of Z rapidity, $y(\mathrm{Z})$.

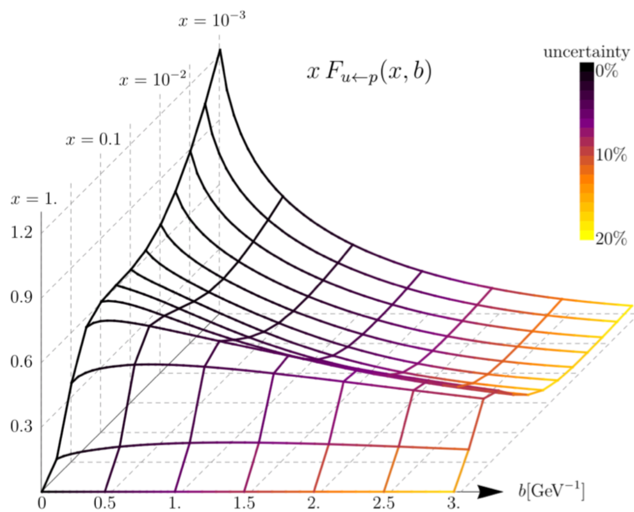


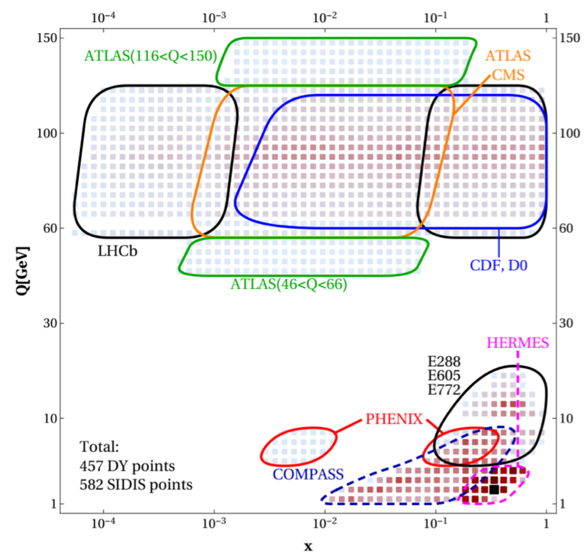
- Three scenarios, assuming no IC, IC allowed and valence-like IC (BHPS).
- A sizable enhancement at forward Z rapidities, consistent with the effect expected if the proton wave function contains the $|uudc\bar{c}>$ component.
- Incorporating these results into global PDF analyses should strongly constrain the large-x charm PDF, both in size and shape – and could reveal that the proton contains valence-like intrinsic charm.
- Test of DGLAP evolution from low Q in DIS to EW scale.

DY neutral current process



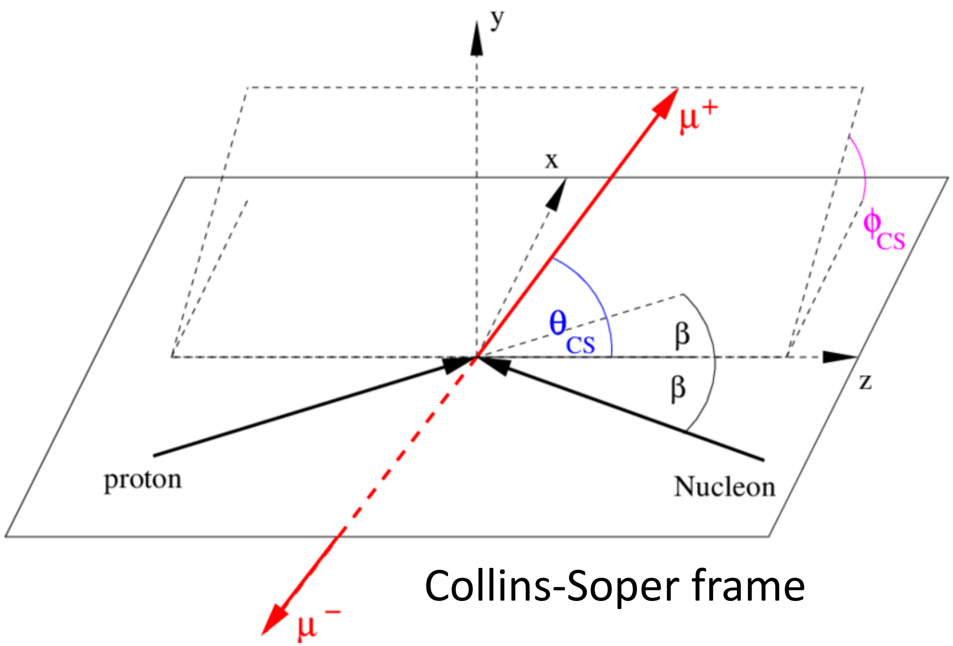
- Rich physics encoded in angular distribution of muons from $\gamma^*/Z \rightarrow \mu^+\mu^-$ decay in the forward region.
- Z-boson cross-section measurements at low Z p_T (< 0.2 m_Z) already used for global analyses of unpolarized TMD PDFs.





JHEP **07**(2020) 117

Angular coefficients



Collins-Soper frame

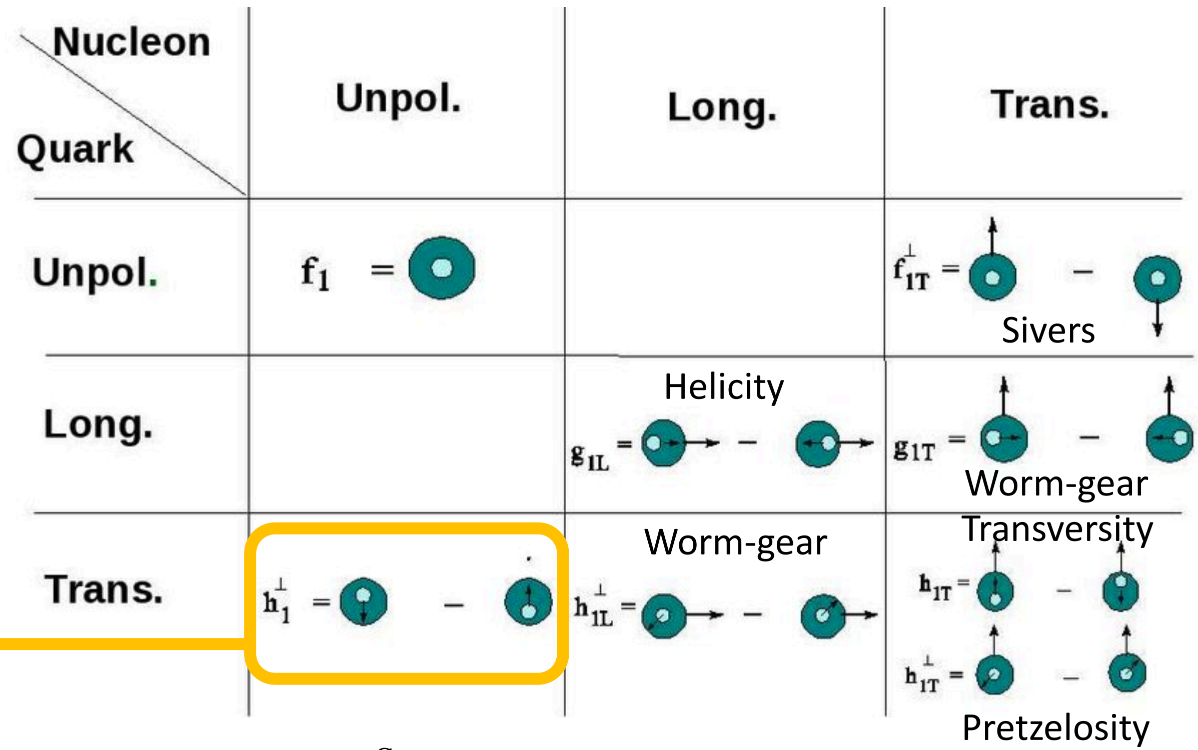
- Production mechanisms for spin 1 particles decaying into dileptons can be expressed using 8 angular coefficients A_i (i =0,… 7).
- *Lam-Tung* relation $\mathrm{A}_0 = A_2$ at LO; can be violated by NP effects, e.g. Boer-Mulders TMD PDF, or even at higher order in FO as well as resummation pQCD calculation.
- A_3, A_4 : V-A structure.

Lepton angular distribution

$$\frac{d\sigma}{d\cos\theta d\phi} \propto (1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi + \frac{1}{2}A_2\sin^2\theta\cos 2\phi$$
$$+A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi.$$

TMD PDFs and DY

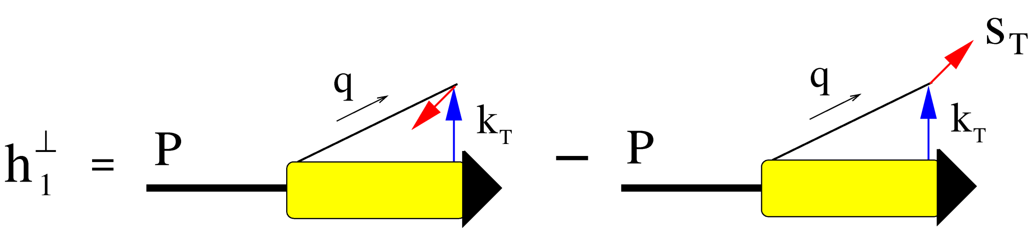
Leading Twist PDFs



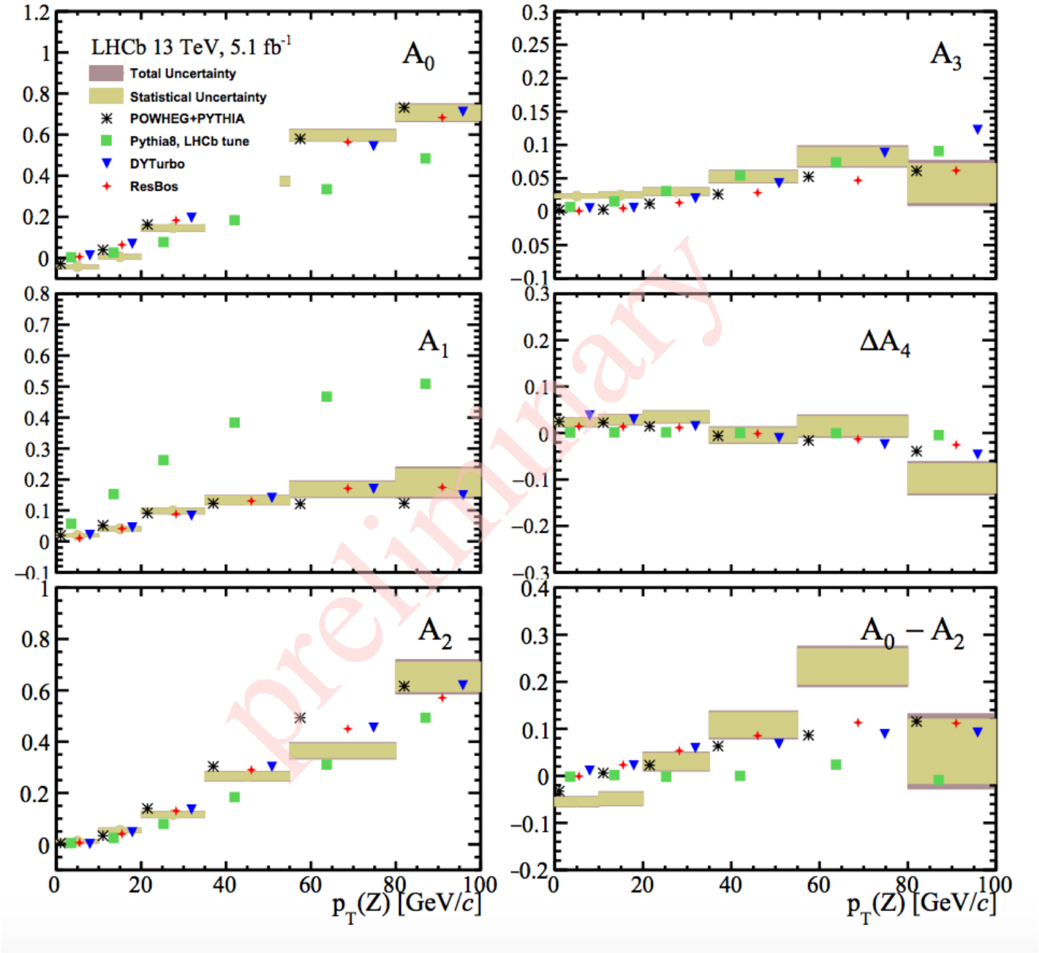
Boer-Mulders Fn

: quark spin-momentum correlation

: can be measured via DY angular distribution at low p_T (cos 2φ modulation) at LHCb.



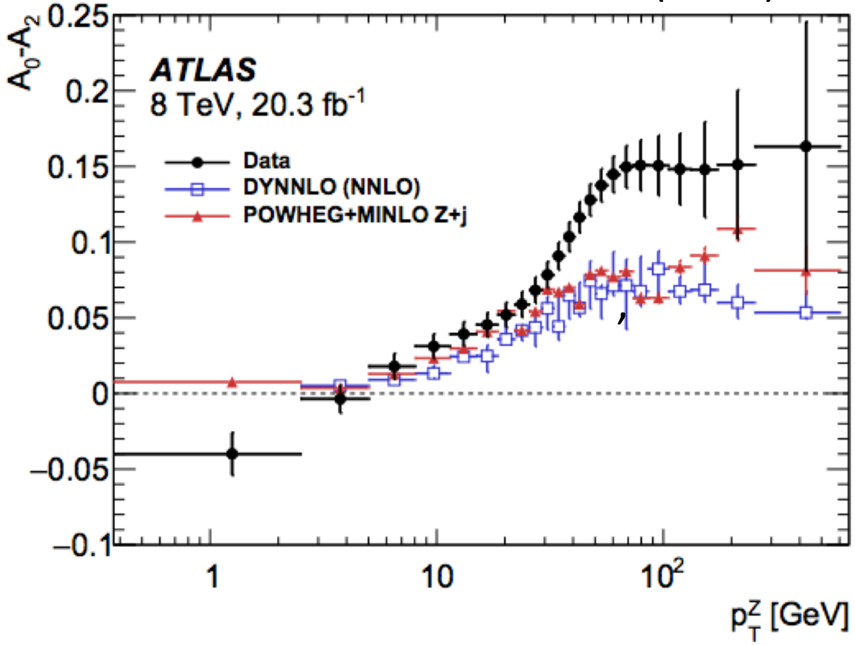
DY angular coefficients



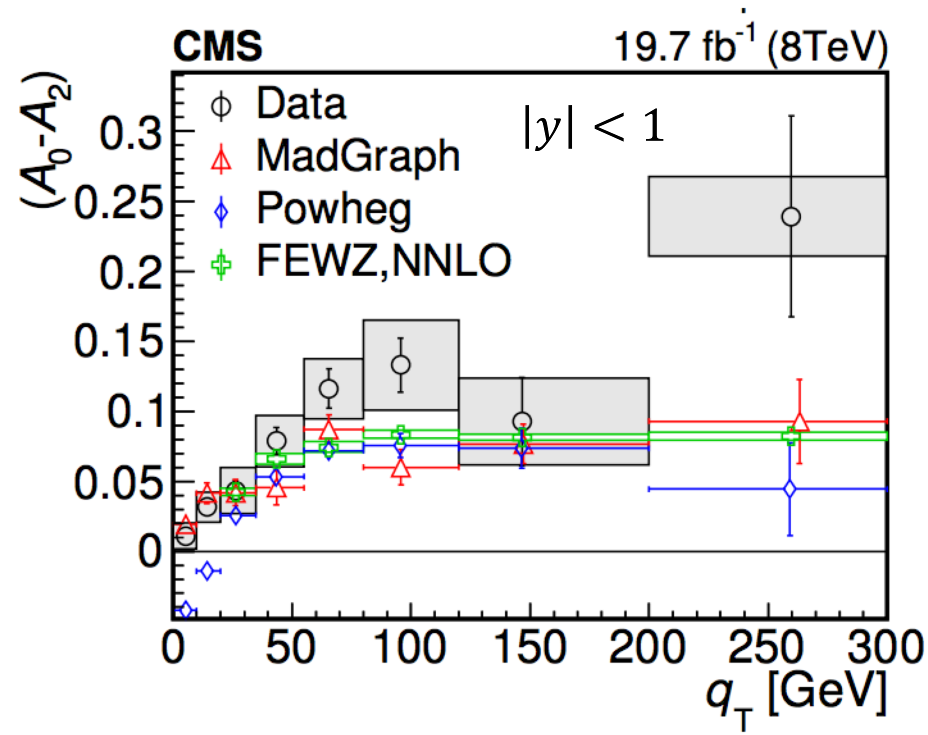
- New LHCb results!
- Overall agreement in trends between data predictions with an except for Pythia.
- Significant violation of Lam-Tung relation observed

- Significant violation of Lam-Tung relation observed;
- consistent with measurements by CMS and ATLAS.

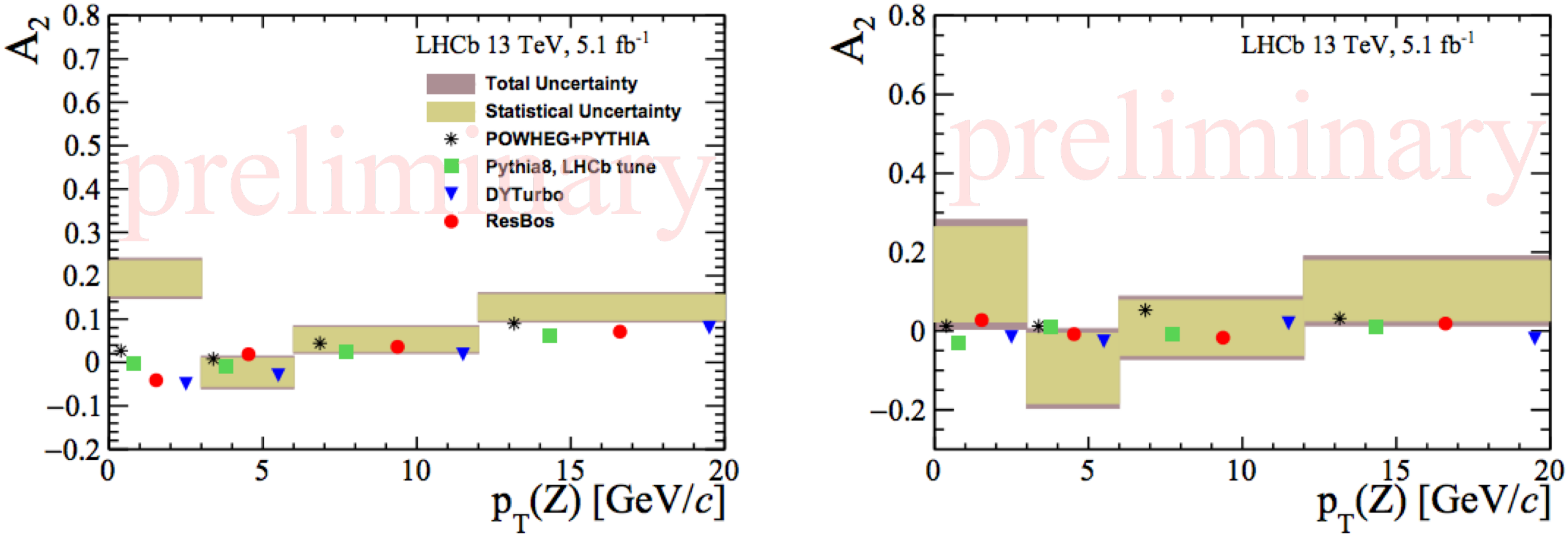
$|y| < 3.5$ JHEP **08** (2016) 159



Phys. Lett. B **750** (2015) 154



$50 < M_{\mu\mu} < 75\ GeV/c^2$ $\qquad$ $105 < M_{\mu\mu} < 120\ GeV/c^2$



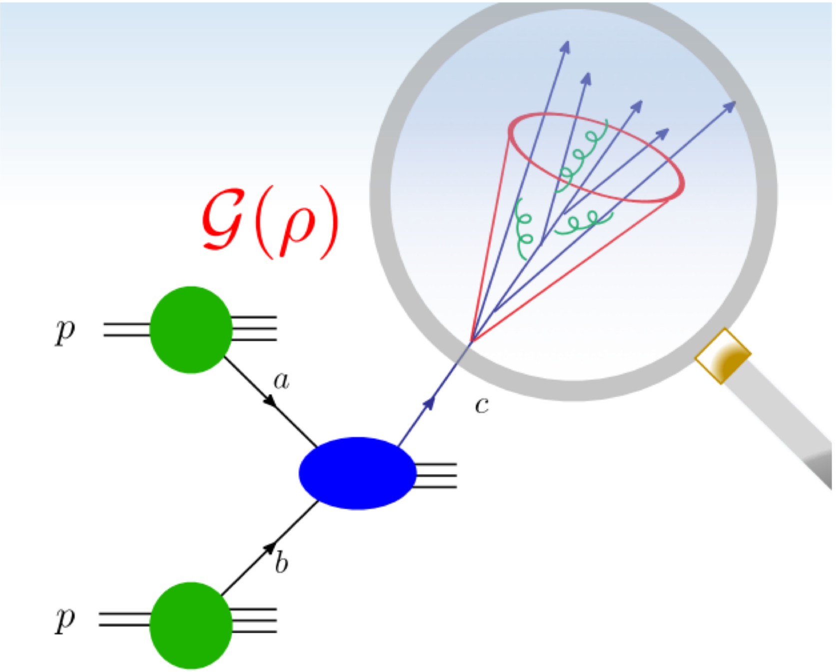
Boer-Mulders TMD PDF

- A_2 in the low p_T region sensitive to the Boer-Mulders TMDPDF
- At $p_T(Z) < 3$ GeV/c, A_2 measured to be ~ 5 times all predictions.
- No phenomenological calculations available.

Jet substructure

Jet substructure ρ

- Jet angularity
- fragmenting jet function (FJF)
- TMD FJF
- …

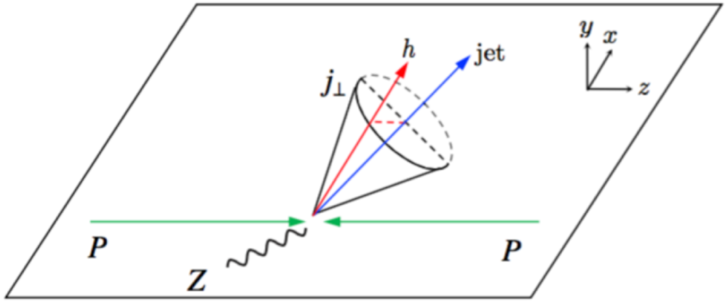


$$\frac{d\sigma^{pp\rightarrow jet\,(\rho)X}}{dp_T d\eta\, d\rho} = \sum_{a,b,c} f_a \otimes f_b \otimes H_{ab}^{c} \otimes \mathcal{G}_c(\rho)$$

Accessing TMD FF using hadrons in jets

$$\frac{d\sigma^{pp\to \text{jet}(h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} = \sum_{a,b,c} f_{a/A} \otimes f_{b/B} \otimes H_{ab}^c \otimes \mathcal{G}_c^h(z_h, \boldsymbol{j}_\perp)$$

$\sim \widehat{D}_{h/c}(z_h, j_\perp, \mu_J)$
: TMD FF



$$z = \frac{p_{jet} \cdot p_h}{|p_{jet}|^2}$$

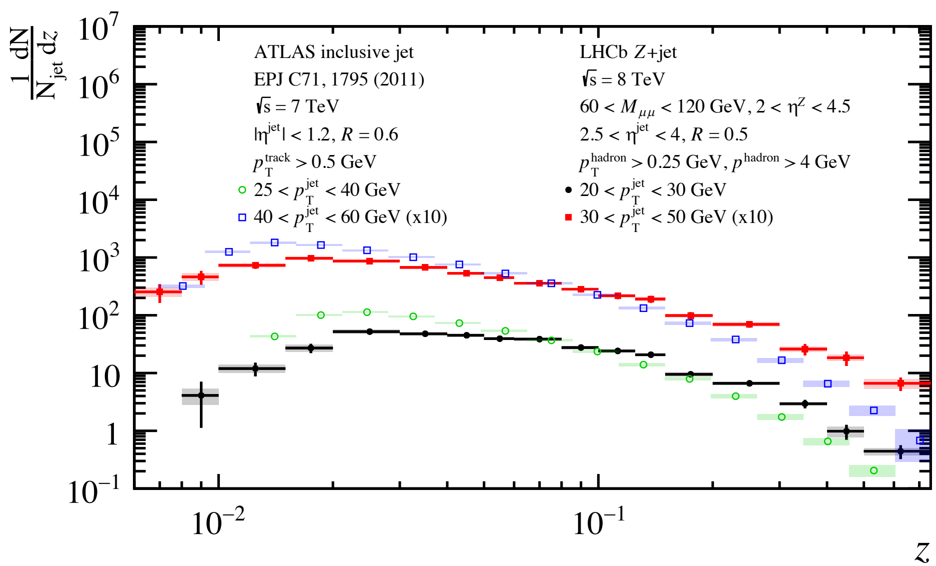
$$j_T = \frac{|p_{jet} \times p_h|}{|p_{jet}|}$$

$$r = \sqrt{(\phi_{jet} - \phi_h)^2 + (y_{jet} - y_h)^2}$$

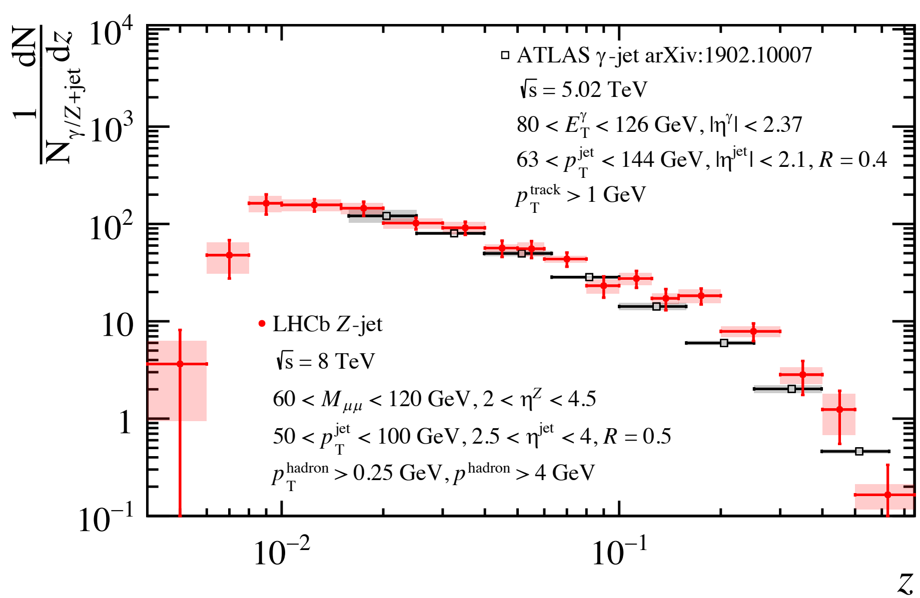
Gluon- vs. quark-initiated jets

- LHCb Z+jets (quark jet) vs. ATLAS inclusive jets (gluon jet)
- Quark-initiated jets are more collimated and takes a larger partonic momentum fraction than gluon jets.

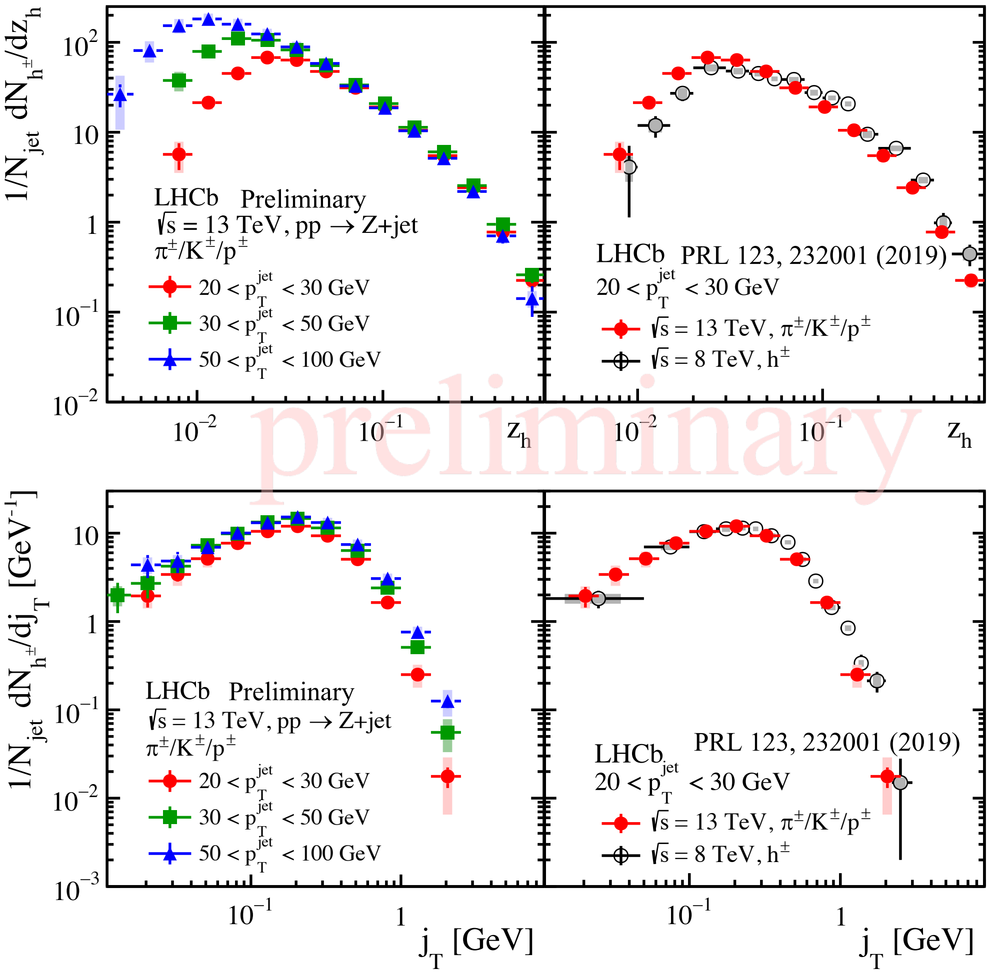
PRL 123, 232001 (2019) - Supplemental material



PRL 123, 232001 (2019) - Supplemental material

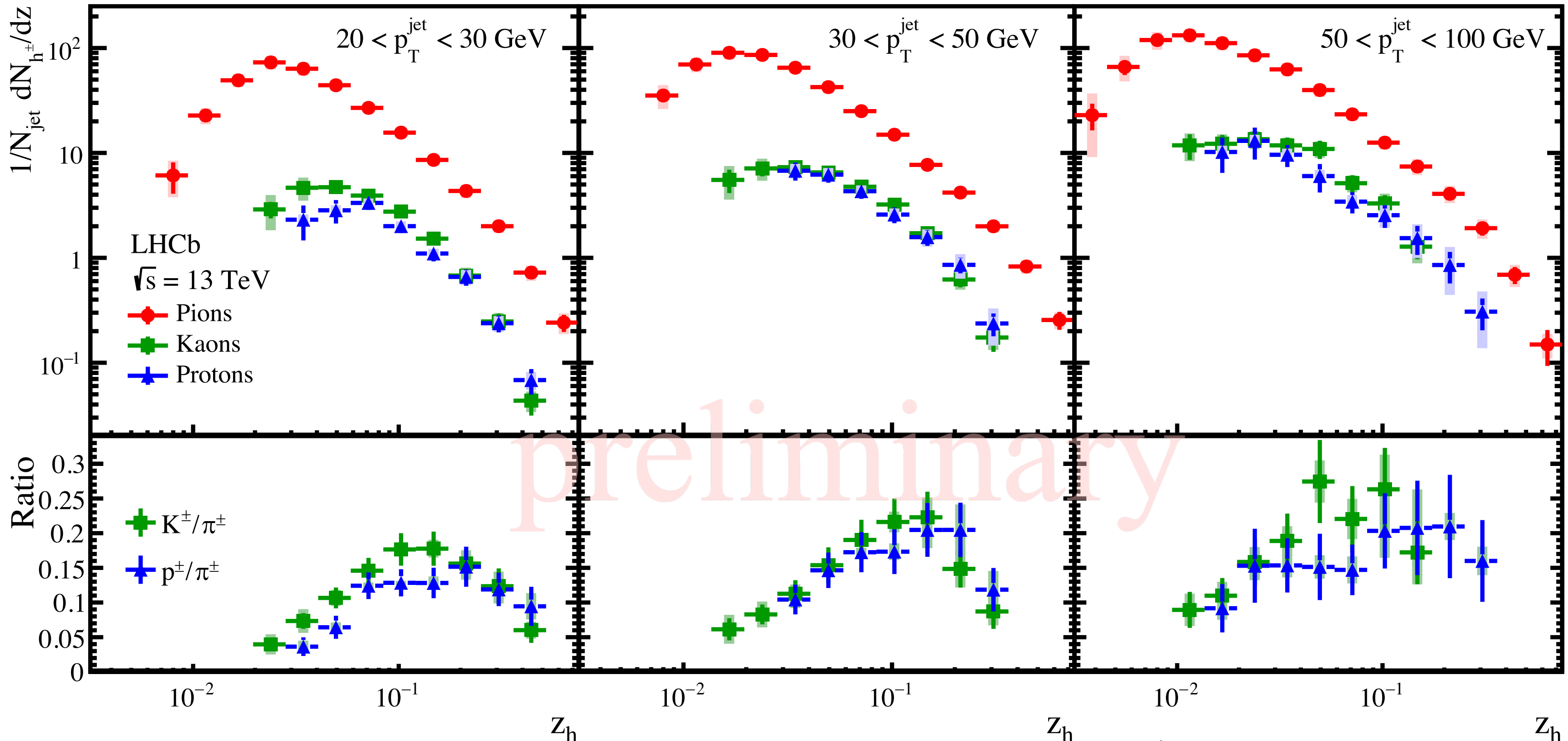


JFF at LHCb



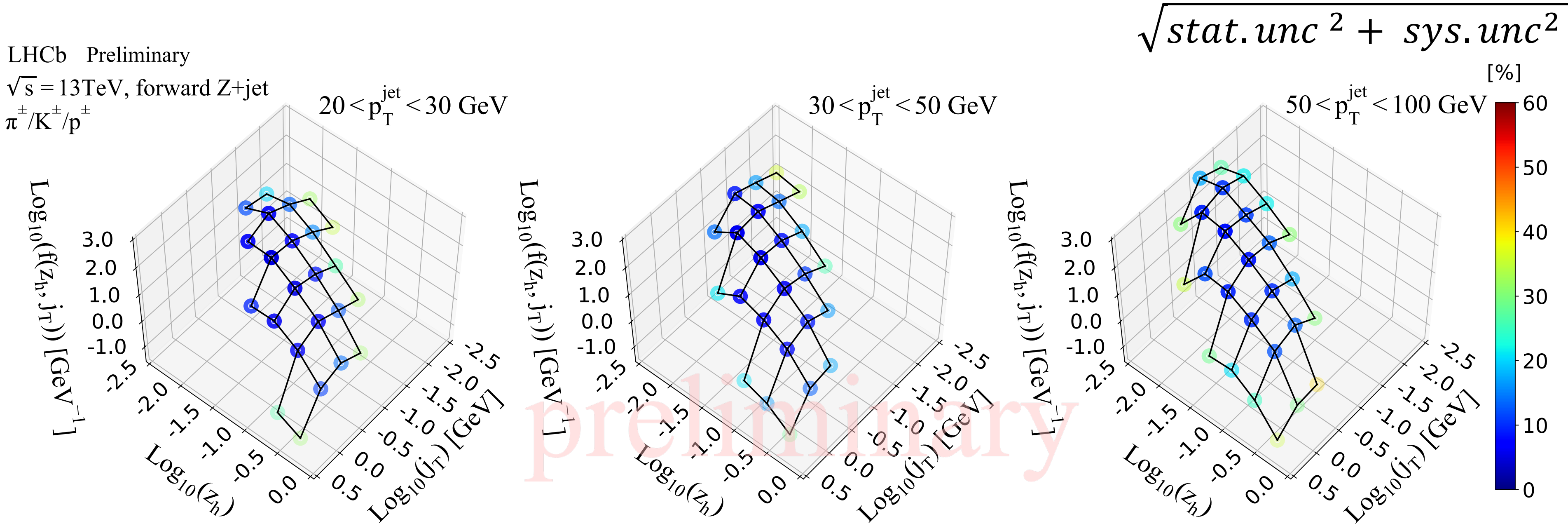
- New results at LHCb!
- Charged hadrons in Z–tagged jets
- At small $z_h < 0.02$, color coherence effects manifest as a humped-back structure.
- Harder jets, higher pT or higher $\sqrt{s}$, produce an excess of soft particles per jet.
- Scaling behavior at large $z_h <$ 0.04.
- Similar pattern in j_T between $\sqrt{s}$ = 8 TeV vs 13 TeV

JFF for $\pi^{\pm}$, $K^{\pm}$ and $p^{\pm}$



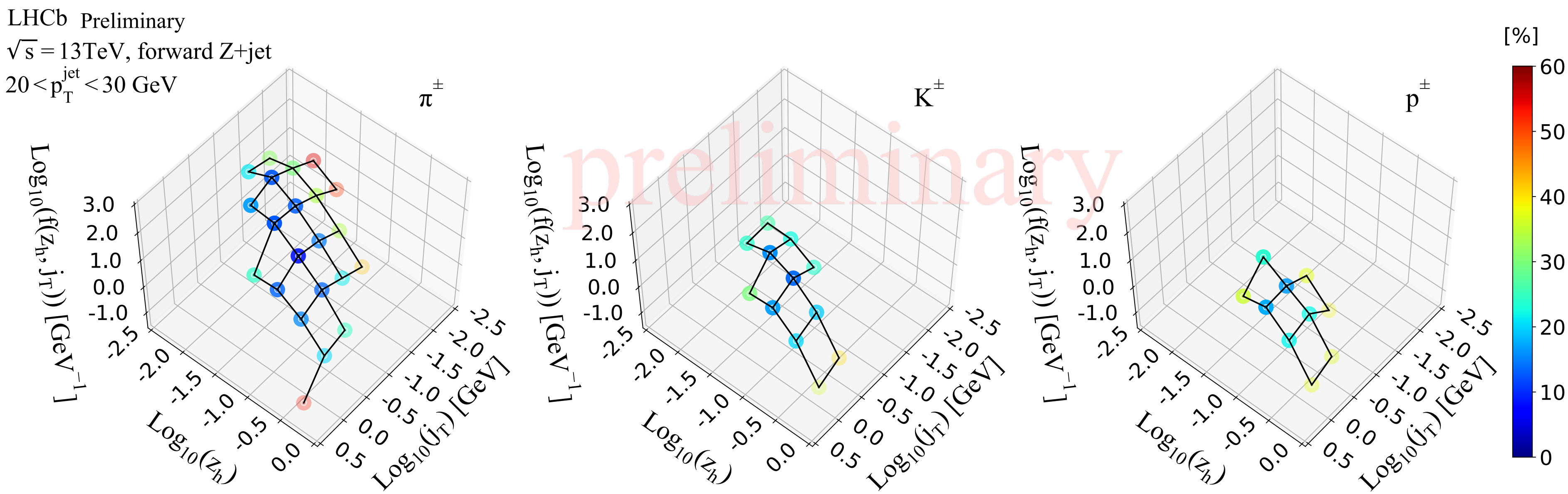
- Charged hadron formation within jets predominantly by $\pi^{\pm}$ due to low mass and flavor of constituent quarks.
- Formation of hadrons at the beginning of parton shower is more suppressed for $K^{\pm}$ than $p^{\pm}$ (protons cross over Kaons at higher z in ratio distributions.)
- Harder jets provide more energy to produce heavier hadrons carrying smaller fraction of jet momentum (later stage of parton splitting) for all hadron species.

TMD JFF for charged hadrons $h^{\pm}$



- Hadrons carrying large momentum fraction along jet axis tend to have large transverse momentum w.r.t. jet axis.
- Centroid of harder jets shifted towards smaller z_h (soft particle production) and larger j_T (fatter jet, increased j_T for given z_h).

TMD JFF for $\pi^{\pm}$, $K^{\pm}$ and $p^{\pm}$



- Joint distributions for pions, Kaons and protons at 20 < jet p_T < 30 GeV/c
- Heavier hadrons produced by harder partons, i.e. larger j_T as well as larger z_h.

Summary and outlook

- ❑ LHCb QCD/EW program performed precision and jet substructure measurements to advance our understanding of nonperturbative dynamics inside proton and hadronization.
- ❑ **Charm jet to Z jet ratio** measurements revealed presence of valence-like intrinsic charm component at large momentum fraction x.
  - Global analyses including new results will constrain charm component in proton PDF.
  - In addition, it can test DGLAP scale evolution from DIS to EW scale at LHC.
- ❑ **DY angular coefficient** measurements saw violation of Lam-Tung relation and hints of NP Boer-Mulders effect for the first time.
  - Results consistent with CMS and ALTAS results that also saw significant violation of Lam-Tung relation.
  - Phenomenological calculations needed to use new results to extract BM fn.
- ❑ **Multi-differential TMD JFF** measured for charged pions, Kaons and protons for the first time.
  - Results shed lights on particle (their flavor composition) dependent parton shower and hadronization processes.
  - Hadrons carrying larger jet momentum fraction in longitudinal direction tend to carry larger transverse momentum w.r.t. jet axis as well.
  - Confirms features shown in measurements at lower $\sqrt{s}$ = 8 TeV; higher jet p_T produces an excess of soft particles in both longitudinal and transverse dimension.
- ❑ Hadronization in heavy flavor jets, excited resonance states under way. Results expected to come out soon.